Annex I

Lago Nero – an example of mountain lake monitoring in a changing Alpine cryosphere

Report on National ICP IM activities in Switzerland

Cristian Scapozza, Luca Colombo, Mattia Domenici, Fabio Lepori, Sebastian Pera, Maurizio Pozzoni, Stefano Rioggi and Andreas Bruder*

Institute of Earth Sciences, University of Applied Sciences and Arts of Southern Switzerland (SUPSI), Campus Trevano, 6952 Canobbio, Switzerland
**corresponding author: cristian.scapozza@supsi.ch*

Background

Deposition of atmospheric pollutants is a key environmental issue for many ecosystems, especially on the southern slopes of the Italian and Swiss Alps which receive substantial inputs from the Po valley in adjacent Italy[1]. Concerning major atmospheric pollutants with acidifying or eutrophying effects, inputs in this region peaked between 1965 and 1980 for sulphur dioxide and around 1985 for nitrogen oxides and probably ammonia[2]. High-alpine catchments are particularly sensitive to atmospheric pollutants but also to other current environmental issues including climate change, mainly as a consequence of their low chemical and physical buffer capacity and their sensitive biological communities. The various and complex effects of atmospheric pollutants and of environmental change in general warrants an integrative monitoring of these ecosystems. The catchment of Lago Nero at the head of Val Bavona in Ticino (Switzerland) was chosen as an ICP IM site due to the postulated sensitivity of its ecosystems to atmospheric pollutants and climate change but also due to its remote location which minimizes direct anthropogenic impacts[3].

The catchment of Lago Nero contains an intact rock glacier on the higher slopes. During build-up, rock glaciers can incorporate and store substantial quantities of deposited atmospheric pollutants. During ice melt, intact rock glaciers then release dissolved chemicals derived from pollutants, often resulting in characteristic chemical signatures[4]. As a consequence, their meltwater can substantially alter chemical composition of receiving surface water bodies, which may affect biological communities[4]. Our study aimed at quantifying ground ice distribution and characteristics in the Lago Nero catchment and its potential to alter the chemical composition of small streams in the catchment.

The study site

The Lago Nero catchment is southwest-facing, with elevations ranging from 2385 m to 2842 m asl. The catchment has an area of 74 ha (lake surface: 13 ha), mainly composed of gneissic bedrock with patches of grassy vegetation and shallow soils. The snow cover period extends approximately from November to June and for a similar period the lake is ice-covered. The mean slope of the catchment is extremely high (84%). The intact rock glacier is located in the south-eastern part of the catchment, with a front

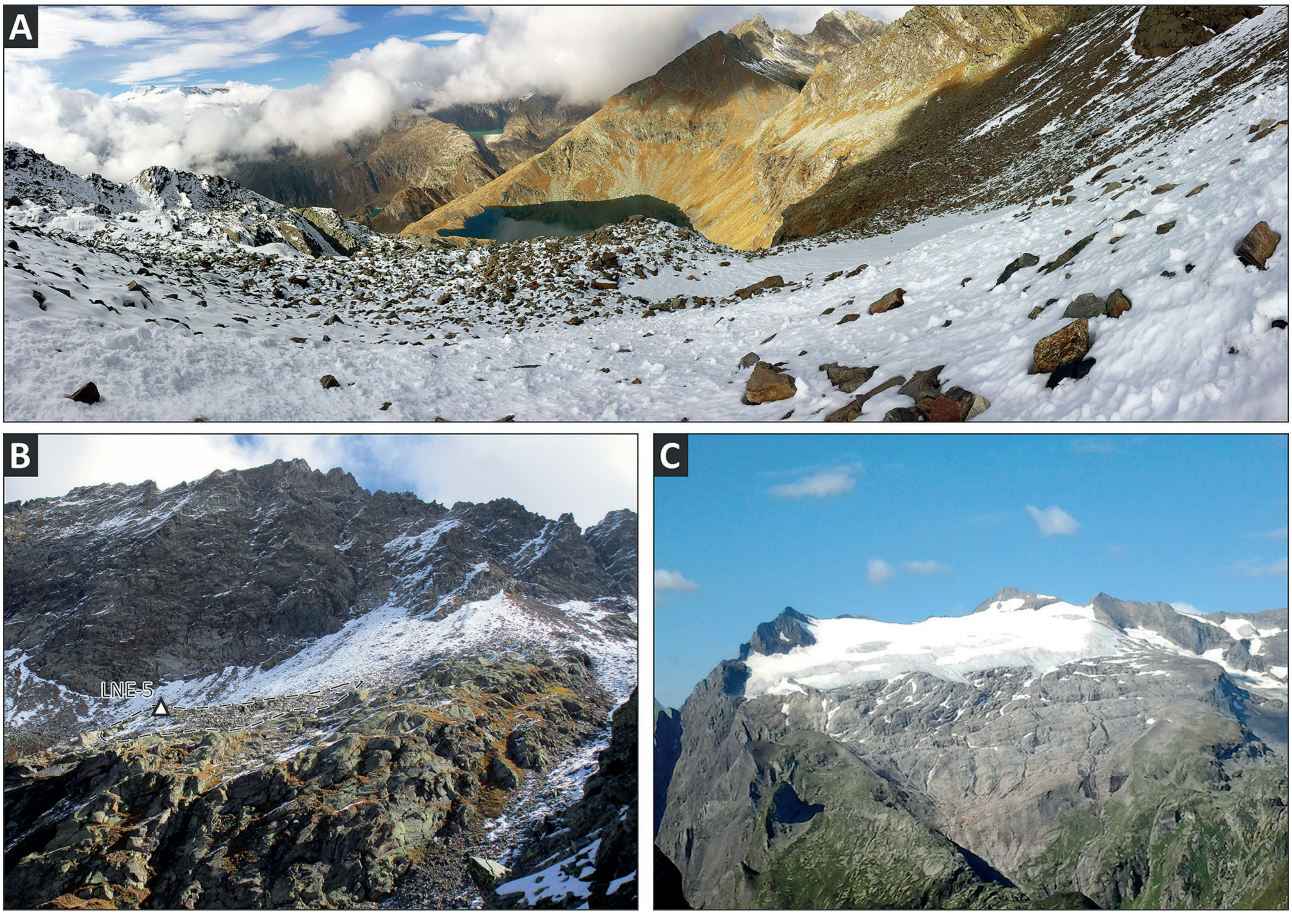

Figure 1. A. View of Lago Nero from the rooting zone of the intact rock glacier in the south-eastern part of the catchment (photo S. Rioggi, 12.10.2015). B. The upper part of the Lago Nero catchment with the intact rock glacier (the front boundaries are dashed), and location of the temperature datalogger LNE-5 (photo C. Scapozza, 12.10.2015). C. View of the Basòdino glacier from the Lago Nero rock glacier (photo C. Scapozza, 17.08.2016).

altitude of 2560 m asl (Fig. 1A, B). Mean Annual Air Temperature (MAAT) and Mean Annual Ground Surface Temperature (MAGST) for the hydrological year 2015/2016 (October 2015 to September 2016), measured close to the lake outflow (temperature loggers LNE-1 and LNE-2 at 2400 m asl; Fig. 2), was 1.5°C and 1.2°C, respectively. Mean Annual Precipitation (MAP) measured at the nearby MeteoSwiss station in Robièi (1896 m asl), is 2420 mm (1981–2010 mean).

Geomorphological mapping and cryosphere monitoring

Cryosphere monitoring at Lago Nero site began in autumn 2015, to characterize the catchment geomorphology, assess the permafrost distribution, and monitor the rock glacier and its contribution to the water chemistry of Lago Nero. Catchment geomorphology was assessed by digital mapping on swissimage orthophoto (©swisstopo) and on swissALTI3D 2m hillshaded Digital Elevation Model (©swisstopo), focusing on landforms, ground texture and the presence of vegetation[5] (Fig. 2). The potential distribution of discontinuous permafrost was mapped using a regional empirical topoclimatic model, based on the variables of aspect and altitude, derived from the rock glacier inventory of the Ticino Alps[6]. Ground Surface Temperature (GST) monitoring started in October 2015 at three locations on the rock glacier (Figs. 1B, 2). Temperatures are measured every two hours with UTL-3 Scientific Dataloggers (Geotest AG, with an accuracy of ± 0.1°C). Water temperature and chemistry of a spring located close to the rock glacier (Fig. 2) are also monitored.

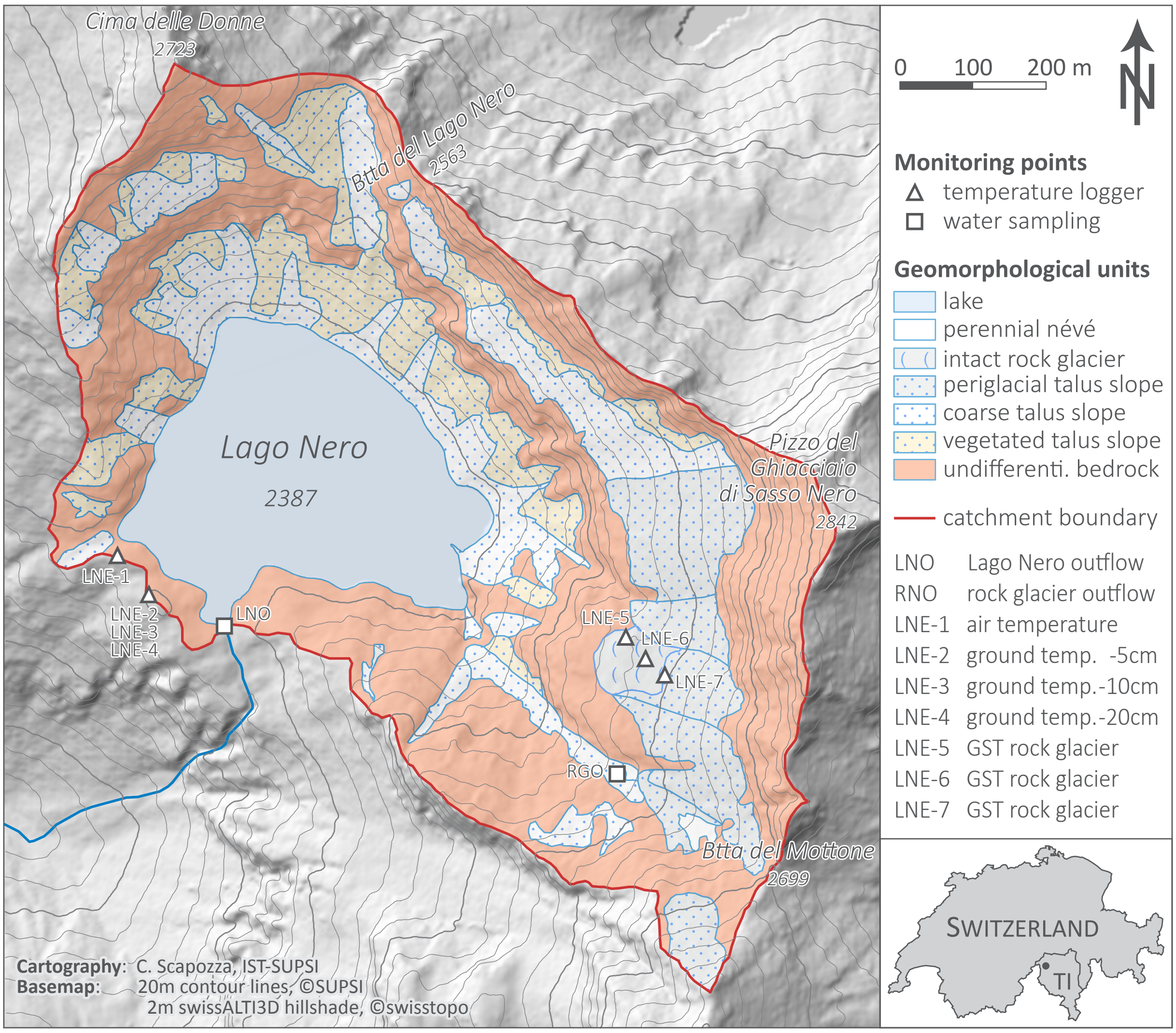

Figure 2. Geomorphological map of the Lago Nero catchment and location of the monitoring points discussed in this paper.

Assessment of local permafrost distribution and monitoring

Local permafrost distribution was assessed using the geomorphological map and the potential distribution of discontinuous permafrost. Geomorphological mapping allowed the identification of two perennial névés and the definition of coarse debris units favourable to potential ground ice storage (permafrost-ice in rock glaciers and talus slopes and debris-covered ice patches), such as intact rock glaciers, periglacial talus slopes and coarse talus slopes (Fig. 2). Considering that permafrost in bedrock usually occurs several hundred meters above permafrost in debris, its presence is improbable in the Lago Nero catchment[7]. The estimation of local permafrost distribution was thus improved by focussing exclusively on the coarse debris units and the presence of perennial névés (Fig. 3). Based on this assessment permafrost is potentially present across 18.75% of the catchment surface (lake surface excluded), corresponding to 0.11 km^2. Considering the high porosity of coarse debris, permafrost zones can store relatively significant amounts of ground ice (20-40% of the total volume) even outside the rock glacier surface[8]. Assuming a warming rate of 0.84°C/100a since 1850[ref 9] and a local lapse rate of 0.6°C/100m, it is possible to consider a belt of permafrost degradation since the end of the Little Ice Age (the last cold period with

Alpine permafrost in climatic equilibrium, ended in 1850) in the Southern Swiss Alps of ca. 230 m in altitude[9, 10]. As a consequence, the zone of potential ground ice melting covers 16.05% of the Lago Nero catchment, representing 85.6% of the total surface with potential permafrost conditions (Fig. 3).

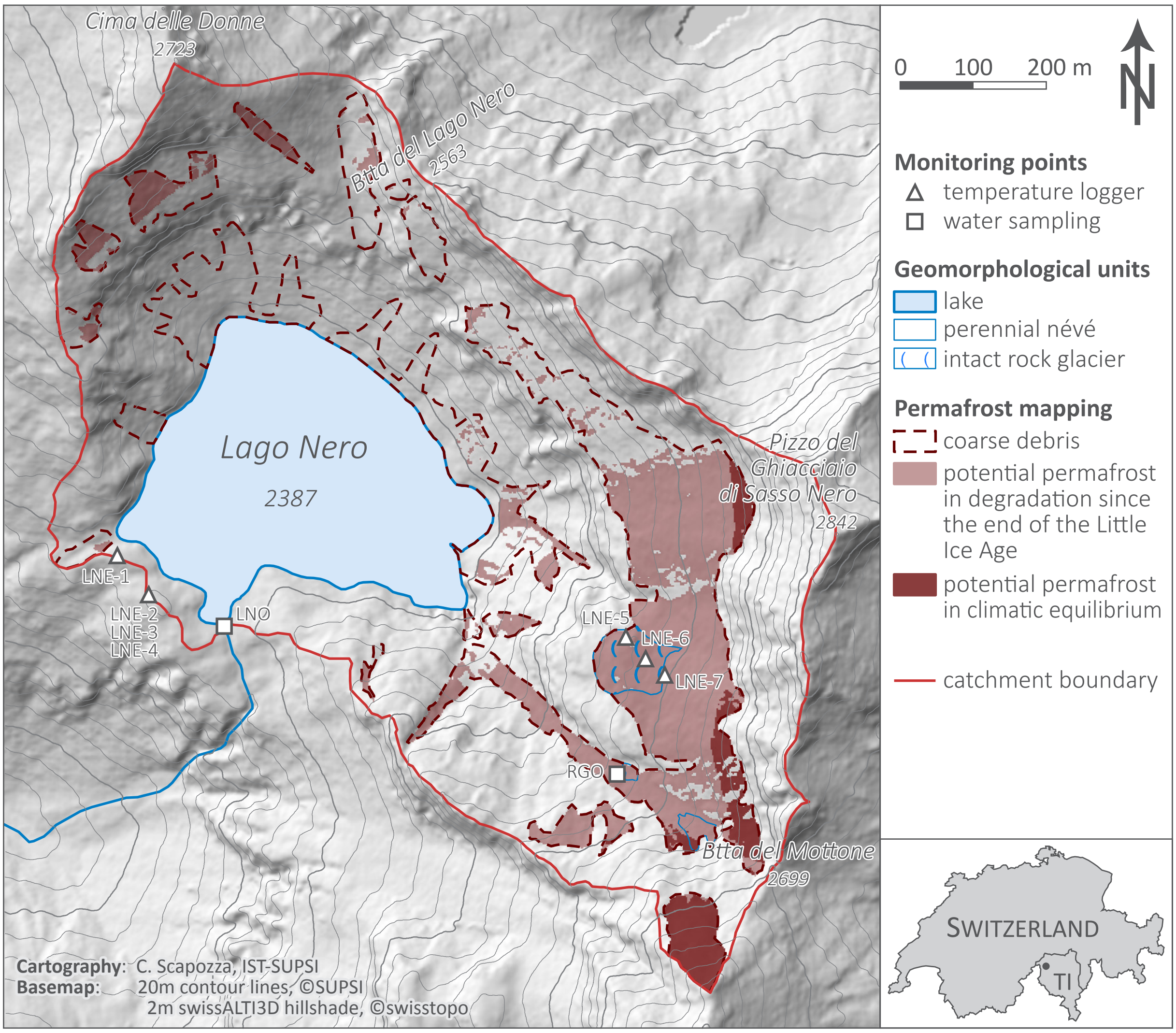

Figure 3. Permafrost distribution in the Lago Nero catchment.

The first results of the thermal monitoring strategy adopted for assessing permafrost degradation and the subsequent ground ice melting indicates a variable temperature regime on the intact rock glacier (Fig. 4). GST for LNE-5 datalogger, located at the top of the rock glacier front (Fig. 1B), presents a very high variability due to snow depletion by wind facilitated by the convex shape of the slope. At this location the freezing potential is very high, with a January-February-March (JFM) mean GST of -6.3°C. The loggers LNE-6 and LNE-7, placed on the body and on the rooting zone of the rock glacier, respectively (Fig. 2), showed a winter equilibrium temperature (WEqT) lower than -2.5°C and a JFM mean GST of -2.3°C and -3.1°C, confirming the probable permafrost presence within this landform[11].

The comparison between water chemistry measured at the rock glacier outflow (RGO) and at the Lago Nero outflow (LNO) shows high amounts of ammonia and sulphate in the periglacial zone with respect to the lake surface water (Tab. 1). Ammonia measured at the RGO exceeded the values measured at the LNO by a factor

> 5.0, sulphate by a factor between 2.1 and 5.7, and nitrate by a factor between 2.0 and 4.0. Measurements performed later during the unfrozen period showed a higher difference between the RGO and the LNO. This is also the case for electrical conductivity, which increased significantly at the RGO from August to October (although these measurements were not carried out during the same year).

With respect to deposition of atmospheric pollutants measured in vicinity to Lago Nero (LND; Table 1), conductivity at the RGO was higher, whereas there were no significant differences concerning nitrate. The main difference was related to sulphate concentrations, which were from 8 to 40 times higher at the RGO. RGO presented higher concentrations of sulphate even in relation to the Maggia and Verzasca rivers, the two main rivers of the Western Ticino Alps, which present mean concentrations of 9.6 and 0.6 mg SO_4 L^{-1} for 2016 respectively[12].

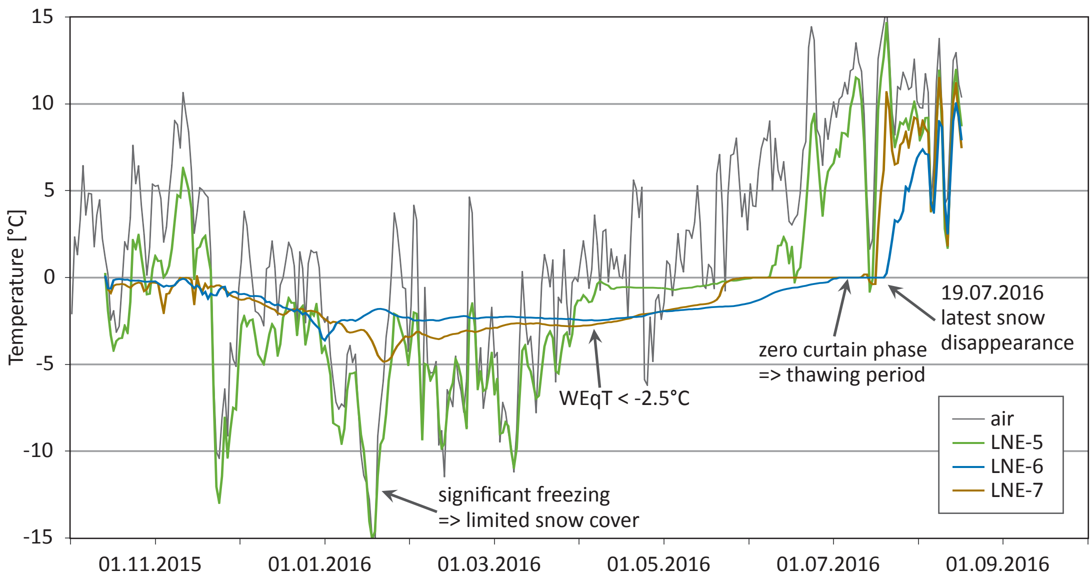

Figure 4. Ground surface temperatures recorded on the Lago Nero rock glacier for the hydrological year 2015/2016. More details in the text.

Table 1. Comparison of water temperature, conductivity and chemistry measured at the rock glacier outflow (RGO) and at the Lago Nero outflow (LNO), and mean atmospheric deposition measured at the Lago Nero (LND).

Parameter		Temp.	Conduct. 20°C	Ammonia [NH_4]	Nitrate [NO_3]	Sulphate [SO_4]
Unit		[°C]	[mS/cm]	[mg N/L]	[mg N/L]	[mg SO_4/L]
12.10.2015	RGO	-	79.0	< l.o.q.	0.4	31.0
	LNO	7.6	14.0	3.1	0.1	2.2
	RGO/LNO	-	5.6	-	4.0	14.1
17.08.2016	RGO	0.4	16.0	38.8	0.2	5.7
	LNO	10.9	15.0	2.3	0.1	2.7
	RGO/LNO	-	1.1	16.9	2.0	2.1
20.09.2016	RGO	0.4	30.0	40.3	0.3	10.7
	LNO	10.0	17.0	7.8	0.1	2.7
	RGO/LNO	-	1.8	5.2	3.0	4.0
2015-2016	LND	-	8.9	225.7	0.3	0.7

Does the cryosphere restitute atmospheric pollutants of the 1960ies to the 1990ies?

Temperature measurements carried out on the Lago Nero intact rock glacier confirmed the permafrost presence within this landform. Considering the ground surface characteristics, aspect and elevation, coarse debris surfaces of the south-eastern part of the catchment are probably perennially frozen and can store significant amounts of ground ice. Permafrost warming since the end of the Little Ice Age probably induced ground ice melting during the last decades, affecting more than 80% of the potential permafrost area of the Lago Nero catchment.

Ground ice melting can substantially alter the physical and chemical characteristics of surface water close to the RGO. Typical high conductivity of cold water emerging close to the rock glacier indicates an accelerated ground-ice melting. Due to the fact that ground ice is in contact with rock debris for long periods (decades, centuries or even millennia), the ionic enrichment explains the higher conductivity of resulting meltwater compared to low-conductivity snowmelt or meteoric waters[13]. Conductivity measurements carried out in the Lago Nero catchment are consistent with this pattern: measurements carried out later in autumn (with less snow melt contributing to flow), showed higher influence of ground ice melting in the water characteristics.

How can we explain the amounts of ammonia, nitrate and sulphate measured at RGO? Mass balance and front variation measurements carried out at the Basòdino glacier, located 5 km southwest of Lago Nero (Fig. 1C), indicate ice accumulation between 1964 and 1994, followed by an almost uninterrupted period of ice ablation (15 of the 20 years between 1994 and 2014 had a negative mass balance)[14]. It is probable that during the period 1964–1994, ice accumulated also in the higher parts of the Lago Nero catchment, as indicated by the number of perennial névés observed on aerial photographs of late summer/beginning of autumn from that period. The presence of perennial névés increases the ground ice mass by their meltwater refreezing or by their debris burial[15]. As a consequence, it is probable that ammonia, nitrate and sulphate was stored in the cryosphere during the 1960ies to 1990ies following deposition of atmospheric pollutants. Their high amounts measured today close to the Lago Nero rock glacier are consistent with the significant melting of ground ice in the last decades caused by warming of Alpine permafrost terrains in Southern Switzerland[16].

Conclusions

Assessment of local permafrost distribution and monitoring, as well as the analysis of physical and chemical characteristics of water in the periglacial belt of the catchment shows that Lago Nero is particularly sensitive to changes in the cryosphere, in particular concerning an increased permafrost degradation and related ground ice melting. The probable storage of ground ice during the 1964–1994 period (deduced from the mass balance of the nearby Basòdino glacier and by the presence of perennial névés) and its significant melting in the last decades, may explain the high conductivity and amounts of ammonia, nitrate and sulphate measured in the outflow of the rock glacier. As a consequence, in high-altitude hydrosystems such as that of Lago Nero, the melting of inherited ground ice may release atmospheric pollutants stored in the cryosphere several decades before. This finding exemplifies the sensitivity of the Lago Nero catchment to climate change.

Acknowledgements

We acknowledge funding by the Air Quality Management Section of the Swiss Federal Office for the Environment (FOEN). Furthermore, we greatly appreciated data provided by MeteoSwiss, Meteotest and the Swiss Federal Institute for Snow and Avalanche Research. We also appreciated the fruitful discussions with Gaston Theis-Goldener, Reto Meier of FOEN and with colleagues from ICP IM, ICP Waters, and our institute.

References

1 Rogora, M., Colombo, L., Marchetto, A., Mosello, R. & Steingruber, S. 2016. Temporal and spatial patterns in the chemistry of wet deposition in Southern Alps. Atmospheric Environment, 146, 44-54.

2 Steingruber, S. 2015. Deposition of acidifying and eutrophying pollutants in southern Switzerland from 1988 to 2013. Bollettino della Società ticinese di Scienze naturali, 103, 37–45.

3 Bruder, A., Lepori, F., Pozzoni, M., Pera, S., Scapozza, C., Rioggi, S., Domenici, M. & Colombo, L. 2016. Lago Nero – a new site to assess the effects of environmental change on high-alpine lakes and their catchments. In: Kleemola S. & Forsius M. (eds), 25th Annual Report 2016. Convention on Long-range Transboundary Air Pollution, ICP Integrated Monitoring. Reports of the Finnish Environment Institute, 29, 52–56.

4 Thies, H., Nickus, U., Tolotti, M., Tessadry, R. & Krainer, K. 2013. Evidence of rock glacier melt impacts on water chemistry and diatoms in high mountain streams. Cold Regions Science and Technology, 96, 77–85.

5 Ambrosi, C. & Scapozza, C. 2015. Improvements in 3-D digital mapping for geomorphological and Quaternary geological cartography. Geographica Helvetica, 70, 121–133.

6 Scapozza, C. & Mari, S. 2010. Catasto, caratteristiche e dinamica dei rock glacier delle Alpi Ticinesi. Bollettino della Società ticinese di Scienze naturali, 98, 15–29.

7 Boeckli, L., Brenning, A., Gruber, S. & Noetzli, J. 2012. Permafrost distribution in the European Alps: calculation and evaluation of an index map and summary statistics. The Cryosphere, 6, 807–820.

8 Scapozza, C., Baron, L. & Lambiel, C. 2015. Borehole logging in Alpine periglacial talus slopes (Valais, Swiss Alps). Permafrost and Periglacial Processes, 26, 67–83.

9 Lambiel, C. & Reynard, E. 2001. Regional modelling of present, past and future potential distribution of discontinuous permafrost based on a rock glacier inventory in the Bagnes-Hérémence area (Western Swiss Alps). Norsk Geografisk Tidsskrif, 55, 220–223.

10 Scapozza, C. & Fontana, G. 2009. Le Alpi Bleniesi. Storia glaciale e periglaciale e patrimonio geomorfologico. Memorie della Società ticinese di Scienze naturali e del Museo cantonale di storia naturale, Lugano, 10, 1–111.

11 Ishikawa, M. 2003. Thermal regimes at the snow–ground interface and their implications for permafrost investigation. Geomorphology, 52, 105–120.

12 http://www.oasi.ti.ch/web/catasti/aria-icpwaters.html, accessed 12.07.2017.

13 Haeberli, W. & Vonder Mühll, D. 1996. On the characteristics and possible origin of ice in rock glacier permafrost. Zeitschrift für Geomorphologie N.F., Suppl.-bd. 104, 43–57.

14 WGMS 2016. Fluctuations of Glaciers Database. World Glacier Monitoring Service, Zurich, Switzerland. DOI:10.5904/wgms-fog-2016-08.

15 Tenthorey, G. 1992. Perennial névés and the hydrology of rock glaciers. Permafrost and Periglacial Processes, 3, 247–252.

16 Scapozza, C., Giaccone, E., Mari, S., Antognini, M., Fratianni, S. & Ambrosi, C. 2016. Il permafrost nelle Alpi Ticinesi (2013/2014 e 2014/2015). Bollettino della Società ticinese di Scienze naturali, 104, 37–44.